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Loss minimization techniques used in distribution network: bibliographical survey

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ABSTRACT

Distribution system provides a link between the high voltage transmission system and low voltage consumers thus I^2R loss in a distributed system is high because of low voltage and high current. Distribution companies (DISCOs) have an economic enticement to reduce losses in their networks. Usually, this enticement is the cost difference between real and standard losses. Therefore, if real losses are higher than the standard ones, the DISCOs are economically penalized or if the opposite happens, they obtain a profit. Thus loss minimization problem is a well researched topic and all previous approaches vary from each other by selection of tool for loss minimization and thereafter either in their problem formulation or problem solution methods employed. Many methods of loss reduction exist like feeder reconfiguration, capacitor placement, high voltage distribution system, conductor grading, Distributed Generator (DG) Allocation etc. This paper gives a bibliographical survey, general background and comparative analysis of three most commonly used techniques (i) Capacitor Placement, (ii) Feeder Reconfiguration, (iii) and DG Allocation for loss minimization in distribution network based on over *147* published articles, so that new researchers can easily find literature particularly in this area.

Contents

1. Introduction

Losses in transmission and distribution networks represent the single largest consumption in any power system. Due to the rapid increase in the demand for electricity, environmental constraints and competitive energy market scenario the transmission and distribution systems are often being operated under heavily loaded conditions and the distribution system loss has become more and more of a concern. The requirement to provide acceptable power quality and enhanced efficiency to achieve all possible economic benefits will create a very favorable climate for the need of loss minimization techniques and innovative operating practices. The total power delivered to the distribution system has been calculated according to the total power generation and power loss of the transmission system. To enhance the efficiency

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Nomenclature

L	energy loss caused by quadrature current in feeder
CkVA	capacitive kilovolt-amperes
KVAr	reactive kilovolt-amperes
kVA	kilo volt-amp
RMS	root mean square
EP	evolutionary programming
ULTC	under-load tap changer
CL	capacitor location, per unit (pu) of total feeder resistance
CR	rated capacitor current, pu of maximum input quadrature current to feeder
$T1, T2\ldots Tn$	time, pu of period of load cycle, during which the input quadrature current equals
$X1, X2, \ldots Xn$	ratio between input quadrature current during time Tn and maximum input quadrature current
R	line resistance in pu
i	reactive current at feeder
X	distance from feeder
LE	energy loss
x	distance measured along the normalized equivalent uniform feeder
$F(x)$	feeder reactive current function
z	control variable
DPSO	discrete particle swarm optimization
I_S	peak reactive current injected into the feeder
r	P.U. length resistance of line
I_{cj}	sizes of shunt capacitors ($i=1,2\ldots\ldots n$)
t	time required to on/off fixed capacitors
OF	objective function ($)
OD	present worth of revenue requirements of one dollar investment, ($/$)
BPSO	binary particle swarm optimization
RC	cost of released kVA capacity ($)
CC	construction cost of all related capacitor installations ($)
τ	power loss reduction time
SC	annual marginal cost of system capacity ($/kW)
PL	power loss savings at time of system peak (kW)
EC	marginal cost of energy losses ($/kWh)
EL	annual energy loss savings (kWh)
Fp, F_E	present worth factors for power and energy losses, which are functions of discount rate, comparison time interval and appropriate cost escalation.
X_{line}	aggregate reactance of the line connecting the load to the feeding substation
$S_{Loss\ ij}$	power loss in line i–j
S_{ij}	complex power from bus i to j
$S_j i$	complex power from bus j to i
$P_q(\tau)$	power loss reduction at time τ
I_c	capacitor current
$a(\tau)$	the substation load time variation
H	matrix to calculate distance between substation to capacitor
bT	reactive load current distribution
I_2	end load current
S	savings ($/yr)
LP	reduction in peak power losses
CC	total cost of capacitors
Kp	factor to convert peak power losses to dollars
Ke	factor to convert energy losses to dollars
δ	load angles
θ	voltage angle
m, q	variables to represent number of buses
F	objective function
Kr	annual cost per unit of the real power loss ($/kW/yr)
P_{load}	active power of load
Q_{load}	reactive power of load
TPC	Taiwan power company
Kc	annual cost per unit of the reactive power injection at bus i ($/kVAR/yr)
Qc	reactive power injection at respective bus
P_B, Q_B	active and reactive power flow in the branch
P_L, Q_L	active and reactive load power
Q_C	capacitor power
CPU	central processing unit
R	resistance of branch
J	complex current flow in branch
Em	component of' $E=R_{bus}I_{bus}$' corresponding to bus m. R_{bus} is the "bus resistance matrix" of feeder before the load transfer which is found using the substation bus as reference.
I_{bus}	the vector of bus currents for feeder
En	similar to Em, but defined for bus n of next Feeder.
P_{DG}	active power of DG
Re	real part of impedance.
V_L	load voltage
P_{rloss}	real power loss of the system.
kp, ke and kq	the cost of power loss at peak-load time (in $/kW), the cost of fuel served for energy losses (in $/kWh) and the cost of reactive sources (in $/kVAr), resp.
τa	fraction of time in load curve
Q_{DG}	reactive power of DG
SCADA	supervisory control and data acquisition

of distribution system loss minimization is the only alternative. Thus it is found that, since last three decades research in distribution systems has been focused on line loss minimization and voltage regulation. Various methods of loss minimization in distribution system are available in the literature but the basic three methods such as (i) Capacitor Placement (generally applicable in high voltage distribution systems) (ii) Feeder Reconfiguration (generally applicable in low voltage distribution systems) and (iii) DG Allocation (more focused to achieve interconnection when small generators exists. For instance, when isolated wind farms or small photovoltaic plants enter the distribution network) are discussed here.

Traditionally, loss minimization has focused on optimizing network reconfiguration or reactive power support through capacitor placement. However, the evolution from passive distribution networks to active due to the insertion of DG presents opportunities. Although planning issues, the regulatory framework and the availability of resources limit Distribution Network Operators (DNOs) and developers in their ability to accommodate distributed generation, governments are incentivizing low-carbon technologies, as a means of meeting environmental targets and increasing energy security. This momentum can be harnessed by DNOs to bring network operational benefits through lower losses delivered by investment in DG [1]. This article incorporates the various approaches made by researchers in order to minimize the

distribution losses and the prolonged study shows that the loss minimization by DG allocation is providing enhanced prospects.

In this bibliography, collection of selected literature from IEEE transactions, IEE proceedings, proceeding of conferences, and leading technical journals such as International Journal of Electrical Power and Energy Systems, Power System Research, Energy etc. is included. Exceptions were made to include publication in other resources if a publication offered a significantly unique, technical viewpoint on the relevant issue.

2. Types of losses

The studies found in the literature can be classified into two approaches:

1. minimization of power losses and
2. minimization of energy losses.

Energy loss deals with fuel burned to produce that energy whereas the peak power loss is important because it has a definite bearing on the equipment ratings to carry the peak load.

3. Capacitor placement

This section contains those publications which are related to Distribution Network Loss Reduction by using Capacitor Placement Technique which was found to be feasibly applicable in high voltage distribution systems. The application of capacitors to electric power systems can be used for:

1. the control of power flow,
2. stability improvement,
3. voltage profile management,
4. power factor correction, and
5. power and energy loss reduction.

The capacitor is a source of reactive power as by reducing the inductive reactance portion of the line loading, it can reduce the reactive losses which can be done by the addition of shunt capacitors. Various authors have done a perceptible work in capacitor placement technique for voltage control and thereafter for loss minimization [1].

The main challenges in this technique are:

1. selection of an appropriate number of capacitor units,
2. allocation of capacitors, and
3. sizing of capacitors to achieve a required result i.e.,
   a. loss reduction,
   b. voltage regulation, and
   c. power flow control.

The advantages of varying the capacitive volt-amp reactive (VARs) in response to the load change have been recognized since 1940s. Before 50s the trend of loss minimization by capacitor placement at the substation was prevailing but from the decade of 50s the trend has been started to install capacitors out on the primary distribution feeders closer to the loads rather than at the substation due to both the availability of pole-mounted equipment and because of the economics favoring the arrangement [2].

3.1. Loss equation

Consider a single line diagram of a uniformly loaded feeder as shown in Fig. 1.

The basic reactive loss given by equation

Total Losses (due to reactive current)

$$= \min \int i^2 R dx = \min \int [I(1-x)]^2 R dx \quad (1)$$

where i is the reactive current at feeder; R is the total resistance and x is the distance from source.

This formula is used in the literature, in various forms for siting and sizing the capacitors so as to achieve minimum losses.

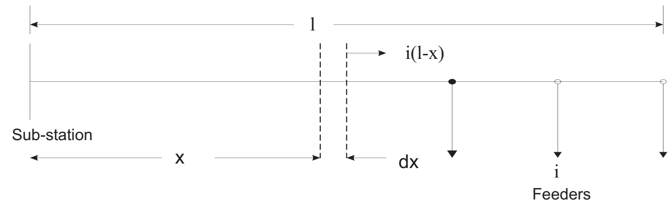

Fig. 1. Single line diagram of uniformly loaded feeder.

3.2. Note worthy contributions

In 1956 Neagle and Samson [3] has presented rules-of-thumb for capacitor allocation. In 1961 Cook [4] has shown an outstanding work by considering the effects of Energy and Peak Power Losses as well as released capacity or reduction in kilovolt-amp (kilo Volt-Amp) demands. In 1968 Duran [6] developed the method which determines conditions when the capacitors are not economically justified. All those approaches suffer from following drawbacks:

1. very restricted reactive-load distribution,
2. wire size of the feeder has been usually assumed to be uniform,
3. voltage control problem was not considered,
4. consideration of limited number of capacitors at a time,
5. solutions obtained under these assumptions may be far from real circumstances, and
6. methods were practically not compatible

In 1981, Grainger and Lee [7] by eliminating many previous shortcomings set forth procedures for sizing and locating fixed shunt capacitors on primary distribution single radial feeder having possibly many sections of different wire sizes and for any known reactive-load distribution along the feeder which may not necessarily either uniformly distributed or concentrated feeders. Whereas in [8] they extend their concepts and modeling procedures to account for both fixed and switched capacitors. After that in 1982 [9] they had proposed voltage dependent methodology for shunt capacitors which allows incorporation of an a. c. load flow program into the procedure for radial feeder compensation. In 1983 Grainer et al. [10] presented continuously controllable, capacitive compensation scheme for primary distribution feeders which assist distribution automation schemes being considered for implementation by electric utilities which rely heavily on substation-based computers for control of *Reactive Power* on primary feeders. But none of the above approaches have accounted for the benefits due to either capacity release, effects of the growth factors, load growth, growth in load factor, voltage rise problems during off-peak period and change in cost of energy. But all those methodologies were not capable of determining the optimal number of capacitors, their type and the optimum bank size selected was not necessarily a standard industry size. In 2008 Ulinuha et al. [39] proposed *Evolutionary-Based Algorithms* which were capable of optimizing large distribution systems with different types of nonlinear loads. In this algorithm the optimal scheduling of Load Tap Changers and switched shunt capacitors for simultaneously minimizing energy loss and improving the voltage profile while taking harmonics into account was

Table 1
Gradual evolution in capacitor placement method.

Author	Type of loss/ application	Specific feature if any	Optimization approaches/ techniques	Optimization function/basic principle	Network	Achievements/merits	De-merits
Neagle and Samson [3]	Power loss/shunt capacitors.	Maximum loss reduction for a single capacitor bank can be obtained when Ckva of the bank is equal to two thirds of the KVAr load on the feeder.	Rules-of-thumb	Total losses $=\int i^2Rdx=\int [I(1-x)]^2Rdx$	Radial circuits with distributed load	Started the trend of moving the capacitors from the substation out to the load areas.	Only peak kilowatt loss savings are considered. Not suitable for larger systems. No guarantee of global optimality
Cook [4]	Power and energy loss/fixed and switched shunt capacitors	Considered the effects of losses as well as released capacity or reduction in KVA demands.	Digital programming	$L=\int_0^{C_L}[(X_1-X_1R-C_R)^2T_1+(X_2-X_2R-C_R)^2T_2+\ldots+(X_1-X_nR-C_R)^2T_n]+\int_{C_L}^1[(X_1-X_1R)^2T_1+(X_2-X_2R)^2T_2+\ldots+(X_n-X_nR)^2T_n]dR$	Radial circuits with distributed load.	Economic location, optimum size, location, and switched capacitors are determined	Fixed cost per capacitor is assumed. Incremental cost is neglected. Reactive losses are neglected Separate optimization of fixed and switched capacitors
Schmill [5]	Power loss/shunt capacitors	Build a search routine in which loss savings are compared for different locations of the capacitor banks until optimum savings are obtained	Load flow Method of calculus	Total losses $=\int i^2Rdx=\int [I(1-x)]^2Rdx$	Uniformly distributed loads and randomly distributed variable spot loads.	Optimum sizes of capacitor banks for specific location. Cost saving.	Uniform wire size. Ignored voltage control problem.
Duran [6]	Power loss/fixed type of Shunt capacitors	Developed the method which determines conditions when the capacitors are not economically justified.	Dynamic programming	Modified form of objective function used by Cook	Radial distribution feeder with discrete lumped loads	Optimum number, location, size and cost saving.	Voltage control problem is not assumed.
Grainger and Lee [7–10]	Power and energy/ fixed and switched capacitors	By eliminating many previous shortcomings set forth procedures for sizing and locating fixed shunt capacitors. Proposed voltage dependent methodology for shunt capacitors which allows incorporation of an a. c. load flow program into the procedure for radial feeder compensation	Computer-based optimization techniques	Equal area criterion	Primary distribution single radial feeder having possibly many sections of different wire sizes	Optimum sizing, siting for any known reactive-load distribution along the feeder which may not necessarily either uniformly distributed or concentrated feeders, number of units and cost of capacitors.	Not considered the benefits due to capacity release, effects of the growth factors, load growth, growth in load factor, voltage rise problems during off-peak period and change in cost of energy.
Ponnavaikko and Rao [11]	Energy loss/fixed and switched capacitors	Suggested a mathematical model which represent cost saving due to energy loss reduction.	Method of Local Variations and dynamic programming	$LE=3\int\{\int (I_s(t)F(x))^2rdx-\int(I_s(t)F(x)-\sum\int(I_S(t)F(x)-\sum I_{cj})^2rdx+\int(I_s(t)F(x))^2rdx\}dt$	Radial distribution feeders	Considered load growth, growth in load factor and increase in cost of energy	Consideration of main feeder branch only Arbitrary number of capacitor banks.
Kaplan [12]	Power and energy loss/fixed and switched shunt capacitors	Developed a method for cost optimization associated with released system capacity	Heuristics based computerized method	$\mathrm{OF}=\mathrm{OD}(\mathrm{RC}-\mathrm{CC})+\mathrm{SCF_P\ PL}+\mathrm{EC\ F_E\ EL}$	Radial distribution feeders	Introduced the method which considers the installation cost of capacitor banks also.	But the procedures are mainly based on heuristics
Grainger and Civanlar [13–15]	Power and energy loss/fixed and switched shunt capacitors	Modeled the distribution systems encountered in practice. Formulated, simplified and solved the problem of volt/var control on general radial distribution systems with lateral branches by proper allocation and sizing of voltage regulators and shunt capacitors in three companion papers.	Dynamic programming	$P_Q(\tau)=r(-I_C^T(H)I_C+2a(\tau)b^TI_C)$	Modeled the distribution systems encountered in practice.	Nonlinear costs of installation of the capacitors are incorporated into the capacitor problem.	Not capable of determining the optimal number of capacitors and their type and the optimum bank size selected was not necessarily a standard industry size.

Table 1 (*continued*)

Author	Type of loss/ application	Specific feature if any	Optimization approaches/ techniques	Optimization function/basic principle	Network	Achievements/merits	De-merits
Salama et al. [16]	Power and energy loss/shunt capacitors	Presented a mathematical analysis of shunt capacitor application in uniform feeder with an end-load condition by considering the requirements in practice.	Dynamic programming	Total losses $= 3xI_c[2 - x(1 - I_2) - I_c]$	Feeders with uniformly distributed loads and end-load are developed.	Conditions of fixed load, growth in the load and the presence of end-load in the feeder.	Becomes complicated for large systems
Bishop et al. [17]	Power loss/shunt capacitors	Gave an examination of seven feeders yielding a significant reduction in real line losses, formulating the justification for future capacitor application efforts.	Analytical Approach	$\min \sum R\|J\|^2$	Feeders with uniformly distributed loads.	Optimum number, location, size and cost saving.	The optimum bank size selected was not necessarily a standard industry size
Suat Ertem et al. [18]	Energy loss/shunt capacitors	Developed a nonlinear model based on the bus impedance reference frame, by taking into account the uncertainty of load	Pattern Recognition Techniques	Sensitivity analysis	Transmission as well as distribution system.	Method suitable for both transmission as well as distribution system.	No assurance of optimality.
Lee [19]	Power loss/Fixed and switched shunt capacitors	Developed a straightforward method, capable of examining the effects of continuous system reconfiguration of switches and capacitors with automated distribution control.	Dynamic programming	$\text{Min} f = \min(P_{r,\text{ loss}})$	Real time Distribution System	Optimum number, location, size and cost saving.	Separate optimization of fixed and switched capacitors
Baran et al. [20]	Power and energy loss/shunt capacitors	A solution method has been implemented that decomposes the problem into a master problem and a slave problem. The master problem is used to determine the location of the capacitors. The slave problem is used by the master problem to determine the type and size of the capacitors placed on the system.	Mixed integer programming	Based on probability	Radial distribution system	Considered discrete nature of capacitor sizes and locations	Becomes complicated for large systems
Ertem et al. [21]	Power loss/shunt capacitors	Developed a mathematical model and presented a solution method for reactive power compensation of distribution circuits having nonlinear loads	Dynamic programming	$\text{Min} f = \min(P_{r,\text{ loss}})$	Radial distribution system	Increase in RMS voltages due to harmonic current flows is incorporated in the problem formulation.	Lengthy and complicated approach.
Baldick et al. [22]	Power and energy loss/shunt capacitors	Theory is compared to load flow calculations and a simple quadratic function was shown to be accurate in estimating the losses	Load Flow analysis	Examined the distribution system loss function and voltage dependence and derived useful approximations analogous to the loss formulae used in the transmission system	Radial distribution system	Considered the conditions of varying the capacitive susceptance of capacitors installed in the system	Iterative approach makes process lengthy.
Salama and Chikhani [23]	Power and energy loss/shunt capacitors	The distribution system voltage profile was kept within the desired limits by proper choice of both shunt capacitors and voltage regulators which provided the values of the reactive power levels to be injected into the distribution system so as to minimize the system losses	Human experts heuristic rules	Based on Gauss-Sidel Method	Radial distribution system	Along with Heuristics knowledge of experienced system is used to obtain optimum saving.	Based on Heuristics.
Hsu et al. [24]	Power Loss/ Shunt capacitors	Investigated optimal capacitor dispatching schedule based on the forecast of hourly loads for the next day, such	Dynamic programming	$\text{Min} f = \min(P_{r,\text{ loss}})$	Radial distribution system	Considered the variable load nature for optimization.	Energy loss and voltage regulation not considered.

		that the total feeder loss in a day can be minimized.					
Abdel-Salam et al. [25]	Power and energy loss/shunt capacitors	Depends on an identification of the sensitive nodes that have a very large impact on reducing the losses in the distribution systems.	Analytical approach.	Sensitivity analysis	Radial distribution system	The method is relatively fast, very effective and gives considerable saving both in energy and in net dollar savings when the costs of the capacitors and their installations are taken into account.	Assumed linear system load.
Shao et al. [26]	Power loss/shunt capacitors	Developed heuristic based rules for loss minimization.	Heuristic rules	Graph search technique	Radial distribution system	Determine the proper size, location of capacitors and shunt capacitor cost.	Based on heuristics
Laframboise et al. [27]	Power loss/shunt capacitors and voltage regulators	Developed an expert system which becomes part of the SCADA system for short and long-term planning of voltage control and loss reduction in distribution systems.	Expert system	Objective function is to minimize power loss.	Radial distribution system	Determine the proper size, location of capacitors and voltage regulators. Cost saving.	Do not get exact solution only approximate solution is obtained
Dan Jiang et al. [28]		Provided a single comprehensive algorithm for distribution system switch reconfiguration and capacitor control.	Simulated annealing- to optimize the switch configuration. Discrete Optimization Algorithm- optimal capacitor control	Minimization of power and feeder losses	Feeders with uniformly distributed loads	Benefits due to the optimal switch configuration and capacitor control were evaluated, both in terms of loss reduction and decreased voltage bandwidth	But it has to suffer from drawbacks of both methods.
Cho et al. [29]	Power and Energy loss/fixed and switched shunt capacitors	Developed a capacitor operation strategy according to the reactive load duration curve of the feeders.	Analytical approach.	Minimize the average power losses	Real time distribution system	determine the proper size, location and switching time of capacitors and shunt capacitor cost	Separate optimization of fixed and switched capacitors
Ramakrishna et al. [30]	Power loss/shunt capacitors.	Proposed a fuzzy inference system to assist the operator for voltage control and Power Loss minimization.	Fuzzy logic.	Fuzzy expert system	Feeders with uniformly distributed loads.	Simplicity of approach and speed makes it a viable option for online VAR control.	The reactive power control problem was decoupled from the voltage regulator problem.
Haque [31]	Power loss/shunt capacitors	Developed a method of minimizing the loss associated with the reactive component of the branch currents	Dynamic programming	The optimal size of the capacitor of the compensated nodes is then determined by optimizing the loss saving equation with respect to the capacitor currents.	Radial distribution system	Simple and easy to use, quick results	May cause erroneous solution for real life system,
Carlisle et al. [32]	Power and energy losses/fixed and switched shunt capacitors	Used a Graph Search Algorithm for the capacitor placement problem and determined a near-optimal solution.	Graph search algorithm	max $S = K_P LP + K_e LE - CC$	Radial distribution system	Considered capacitor sizes as discrete variables and uses standard sizes and exact capacitor costs.	Only the balanced load conditions are assumed with the real power flow as constant.
Deng et al. [33]	Real power losses/ shunt *capacitors.*	Proposed an approach with fuzzy variables which incorporates the load uncertainty in optimizing capacitor on/off status	Fuzzy logic	Objective function is to determine the optimal combinations of adjustable capacitor banks to compensate the reactive load demand.	Radial distribution system	Uncertain load values were represented as trapezoidal fuzzy numbers via fuzzy sets. Fast speed of calculations	Do not meet robustness requirements.
R. H. Liang 2003 [34]	Real Power Losses/ Fixed and switched capacitors.	Presented fuzzy-based reactive power and voltage control in a distributed system	Fuzzy logic	To find the combination of main transformer LTC positions and capacitor on/off switching operations in a day, such that the voltage deviations at the secondary bus of main transformer become as small as possible, while the reactive power flows through the main transformer and *Losses* at feeders become as little as possible.	Radial distribution system	Fast and accurate in determining the size and location	Separate optimization of fixed and switched capacitors
de Souza et al. [35]	Energy loss/*fixed* and switched capacitors.	Proposed a Micro Genetic Algorithm (MGA) in conjunction with Fuzzy Logic (FL) for solving the capacitor placement problem.	Micro Genetic Algorithm in conjunction with Fuzzy Logic	The objective function includes economic savings obtained by an Energy Loss Reduction in contrast with acquisition and	Radial distribution system	Cost saving, capacitor placement, loss minimization.	Complicated methodology.

Table 1 (*continued*)

Author	Type of loss/ application	Specific feature if any	Optimization approaches/ techniques	Optimization function/basic principle	Network	Achievements/merits	De-merits
				installation costs of fixed and switched capacitors.			
Carpinelli et al. [36]	Power loss/shunt capacitors	Developed capacitor placement procedure to minimize the Power Losses	Dynamic programming	Loss minimization	Radial distribution system	Capacitor placement, Considered the impact on the harmonic distortion of bus voltages.	Cannot be directly applied given the size, complexity and the specific characteristics of distribution systems
Venkatesh et al.[37]	Power loss/shunt capacitors	Proposed a single dynamic data structure for an EP Algorithm that handles the problems of siting and sizing of new shunt capacitors simultaneously while considering transformer taps, existing reactive-power sources and reconfiguration.	Evolutionary programming.	Fuzzy based objective function.	Radial distribution system	Considered different load levels and time durations	Energy loss is not considered
Haghifam and Modares [38]	*Energy and peak load loss*/fixed and switchable capacitors	Developed an efficient Genetic Algorithm with a new coding as two rows of chromosome used for optimization in simultaneous allocation of fixed and switchable capacitors	Genetic Algorithm	Capacitor cost was considered in the cost function.	Radial distribution system	Time variation and uncertainty of load were also involved in problem formulation	Separate optimization of fixed and switched capacitors
Ulinuha et al. [39]	Energy and peak load loss/fixed and switched shunt capacitors	Proposed EAs which were capable of optimizing large distribution systems with different types of nonlinear loads.	Evolutionary-Based Algorithms (EAs)	Optimal scheduling of LTCs and switched shunt capacitors for simultaneously minimizing *Energy Loss* and improving the voltage was performed.	Radial distribution system	Considered Time variation and uncertainty of load. Improving the voltage profile while taking harmonics into account.	Separate calculations are required for power and energy loss.
Jong-Young Park et al. [40]	Energy Loss/Fixed and switched Shunt Capacitors	The effect of device lifetime on the switching operation of devices such as ULTC transformers or switched capacitors were added in the objective function as a function of the annual number of operations of the device.	Genetic Algorithm	$P_L = \sum\sum V_m V_q Y_{mq} \cos(\theta_m \theta_q - \delta_{mq})$	Large radial distribution system	Expected device lifetimes are included in the formulation,	Becomes complicated for large systems
Eajal et al. [41]	Power loss/shunt capacitors	Minimized the overall cost of the total Real Power Loss and that of shunt capacitors while satisfying operating and power quality constraints	Particle Swarm Optimization	$F = K_r P_{loss} + \sum K_C Q_C$	Small radial distribution system	Developed Hybrid PSO Algorithm to enhance the efficiency in achieving solution.	Not Suitable for Large system.
Vahid Farahani et al. [43]	Energy loss/ shunt capacitors	presents a joint optimization algorithm for both conductor replacement of overhead lines and capacitorplacement to minimize energy losses in the presence of harmonics throughout the distribution system, such that both individual and total harmonic distortion of bus voltages are kept within the acceptable levels.	Discrete genetic algorithm	$P_B + jQ_B = \sum(P_{L+} jQ_L - Q_C)$	20-kV realistic overhead distribution network in Sirjan city-center in Iran.	Application Capacitor placement and conductor replacement simultaneously.	Not suitable for large system.

Table 2
Gradual evolution in network reconfiguration method.

Author	Type of loss	Reconfiguration approach	Optimization techniques	Objective function/basic principle	Network	Achievements/merits	De-merits
Merlin and Back [57]	Power loss	Starts with a meshed network by initially closing all switches in the network. The switches are then opened one at a time until a new radial network is reached.	Exhaustive search techniques.	Branch and bound method	Radial topology, typical of urban distribution systems.	Final network configuration is independent of the initial status of the switches. Solution process leads to the optimum or a near-optimum solution.	Method involves approximations. Network voltage angles are assumed as negligible. Losses associated with line equipment are not considered
Shirmohammadi and Hong [58]	Resistive power loss	Starts by closing all the network switches which are then opened one after another by determining the optimum flow pattern in the network.	Heuristic approach	min $\sum R\|J\|^2$	Realistic distribution networks	Avoids approximations, Convergence to the optimum or a near-optimum solution, Final network configuration is independent of the initial status of the switches.	The environments under which the calculations are made do not correspond to the actual operating conditions.
Civanlar et al. [59]	Power loss	Determination of the loss change due to a switch exchange.	Load flow based approach	$\text{Power loss} = R_e\{2(\sum I_i)(E_m - E_n)^2\} + R_{loop}\|\sum I_i\|^2$	Realistic distribution networks	Suggests a filtering mechanism for eliminating those switching options which would not yield loss reduction	Multiple switching operations were beyond the scope of his scheme
Sarfi et al. [60]	Power loss	Commences the search for a minimal loss network configuration while the distribution system is partitioned into subsystems.	Dynamic programming.	Based on network partitioning theory.	Meshed distribution networks	Overcomes the size restrictions imposed by previously described reconfiguration techniques.	Algorithm gives a near optimal solution but method does not work so well in the case of load variation.
Ji-Yuan Fan et al. [61]	Power loss	Determined the switch exchanges within a loop for minimum line losses, and utilized a heuristic scheme to develop the optimal switch plan with minimum switch operations to achieve transition from the initial configuration to optimal configuration.	Heuristic approach	Single-loop optimization technique.	Meshed distribution networks	Loss reduction. Installation and switching costs Reduction. Simple and effective scheme to efficiently determine the switch exchanges within a loop for minimum	Simultaneous switching of the feeder reconfiguration is not considered.
Taleski et al. [62]	Power and energy loss	Reconfiguration is performed by closing the open tie switch that defines the loop, and opening the switch in the branch that produces maximum energy loss saving.	Heuristic approach	Branch exchange techniques	Radial network analysis	Provides an alternative to the power minimization methods for operations and planning purposes	Complicated mathematical techniques due to the combinatorial nature of the problem. Large computational time is needed
Kashem et al. [63]	Real power loss.	The trained ANN models determine the optimum switching status of the dynamic switches along the feeders of the network, which thereby reduce real power loss by network reconfiguration.	Artificial neural network (ANN)-approach	The objective is to determine the switching status of the dynamic switches in the feeders that provide a minimum loss configuration to network.	Small radial distribution system	Proposed method is not dependent on the system size. The proposed ANN model can provide a fast prediction of optimal or near-optimal system configuration.	Applied on Dynamic switches only. No assurance of optimum solution
McDermott et al. [64]	Power loss	Starts with all operable switches open, and at each step, closes the switch that results in the least increase in the objective function.	Heuristic nonlinear constructive method	The objective function is defined as incremental losses divided by incremental load served	Radial network.	Algorithm differs from most others, by constructing the system from scratch, rather than performing switch exchanges or sequential switch openings.	Fast but may trap into local minima. Do not guarantee to find out the global optimum in finite running time
Kashem et al. [65,66]	Power loss	Starts with generation of limited number of switching combinations and the best switching combination is determined then an extensive search is employed to find out any other switching combination that may give rise to minimum loss compared to the loss obtained in the first stage.	Dynamic programming.	$\text{Total loss} = \sum(r_L(P_L^2 + jQ_L^2)/V_L^2)$	Medium Radial distribution system.	Efficient for continuous reconfiguration for loss reduction. Requires very less computer time as well as memory.	Not suitable for large systems

Table 2 (*continued*)

Author	Type of loss	Reconfiguration approach	Optimization techniques	Objective function/basic principle	Network	Achievements/merits	De-merits
Ramos et al. [67]	Power loss	It takes into account the status of all branches in the network and concurrently introduced some approximations in order to reduce computation time.	Linear programming	$\min \sum R\lvert J\rvert^2$	Small, medium and large distribution system.	Provides effective solution which does not require load flow throughout the process, Simple technique, Requires less computation time	Solution depends on approximations
Jeon et al. [68]	Power loss.	The proposed method augment the cost function with the operation condition of distribution systems, improve the perturbation mechanism with system topology, and use the polynomial time cooling schedule, which is based on the statistical calculation during the search for solution	Simulated annealing	$\text{Total loss} = \sum(r_L(P_L^2+Q_L^2)\ /V_L^2)$	Real distribution system of the Korea Electric Power Corporation (KEPCO).	Well suited for a large combinatorial optimization problem. It can avoid local minima by accepting improvements in cost.	It often requires a elaborate cooling schedule and a special strategy to obtain solution Applicable only for symmetrical systems and constant loads.
Augugliaro et al. [69]	Power loss	Proposed control strategy of the open-closed status of the tie-switches.	Based on neural networks and a deterministic Algorithm.	The objective can be fulfilled by performing a centralized control strategy in which the status of each tie-switch depends on the current loading condition of the network.	Radial distribution networks	The approach represents the first step towards a complete automation of distribution system. Low cost and the guarantee, in normal operating conditions of radial operation while supplying complete loads.	The local control is less accurate than the centralized control in the identification of the optimal solution.
Ching-Tzong Su [70]	Power loss	Method is simple and based on stochastic searches, in which function parameters are encoded as floating-point variables.	Mixed-Integer Hybrid Differential Evolution (MIHDE) method.	The objective function is $\text{Min} f = \min(P_{r,\ \text{loss}})$	Practical distribution network of the Taiwan Power Company (TPC).	Proposed method provides both Power loss and enhanced voltage stability. It determines system topology that reduces the power loss according to a load pattern.	May give a optimum solution but computationally very expensive and the operations will be much slower than heuristic methods.
Hernan Prieto Schmidt et al. [71]	Power loss.	The integer variables represent the state of the switches and the continuous variables represent the current flowing through the branches. The standard Newton method is used to compute branch currents at each stage within the integer search	Mixed-integer nonlinear optimization	Branch exchange type algorithm	Real-size large distribution system	Suitable for real size distribution systems in an attempt to achieve the advantages of both network restructuring as well as capacitor placement to minimize the losses. The search procedure is fast.	Method does not guarantee the optimality.
Golshan and Arefifar [72]	Energy and power losses	Method is based on *Tabu Search* to solve more comprehensive distributed-generation planning problem including simultaneous distributed generation sources and network configuration planning.	*Tabu Search*	$\text{Cost function} = k_p P_o(z_o) + k_e \sum \tau a P(z) + k_q \sum \lvert q\rvert$	Medium and large distribution system.	Cost saving. Technique allows the search to go beyond the local optimal points while still making the best possible move in each iteration. Makes extensive use of memory structures.	It could not give any guarantee for the convergence property.
Siti et al. [73]	Power loss.	Method uses the neural network in conjunction with a heuristic method which enables different reconfiguration switches to be turned on/off and connected consumers to be switched between different phases to keep the phases balanced.	Heuristic method, Neural Network is adopted for the network reconfiguration problem.	$\text{Total loss} = \sum(r_L(P_L^2 + jQ_L^2)/V_L^2)$	Low-voltage and medium-voltage levels of a distribution network	Phase balancing, Loss minimization problem	Not suitable for large systems.
Chung-Fu Chang [74]	Power loss.	Method solves the optimal feeder reconfiguration problem, the optimal capacitor placement problem and the problem with a combination of the both.	Ant Colony Search Algorithm	The objective function is, $\text{Min} f = \min(P_{r,\ \text{loss}})$	Practical distribution network of Taiwan Power Company (TPC)	Shows significantly enhanced optimization capability.	Computational time required is more.
Queiroz and Lyra [75]	Power loss and energy loss.	Solved larger optimization problem which would be solving network reconfiguration problem to suit each of the significant load variations.	*Adaptive hybrid genetic algorithm*	$\text{Total loss} = \sum(r_L(P_L^2 + Q_L^2)/V_L^2)$	Small, medium and large radial distribution systems.	Method deals with energy flows instead of only instantaneous power flows.	Considered only fixed topologies for either peak or average loads.

						Provides a good trade-off between loss reduction and switching operations.	
Yuan-Kang Wu et al. [76]	Power loss	It aims at achieving the minimum power loss and incremental load balance factor of radial distribution networks with distributed generators.	Ant Colony Algorithm	$\text{Power loss} = \sum(r_L(P_L^2+jQ_L^2)/V_L^2)$	Distribution network of TPC.	Avoids premature convergence. Strong global search ability.	Becomes complicated for large systems
Rao et al. [77]	Power loss	Algorithm uses a stochastic random search instead of a gradient search which eliminates the need for derivative information. Simulations	Harmony search algorithm	The objective function is, Min $f = \min(P_{r,\,\text{loss}})$	Medium and large-distribution networks	Converge to optimal solution very fast even for a large system.	Guaranteed a globally optimal solution but needed an exhaustive search.
Taher Niknam et al. [78]	Power loss	A fuzzy system based on some heuristics is designed to adaptively adjust the parameters of DPSO and BPSO during the optimization process to improve the overall performance. The Nelder–Mead is a simplex search method that has been widely used in unconstrained optimization problem	New fuzzy adaptive particle Swarm optimization (NFAPSO)	$\text{Power loss} = R_{\text{loop}}\lvert\sum I_i\rvert^2$	Medium and large-scale distribution networks.	Shows high accuracy and convergence rate. Independent on the initial status of network switches. Algorithms run time increases when the number of control variables increase.	Method does not guarantee the optimality.
Akbar Bayat [79]	Power loss	The algorithm starts with expanding a sub network through tracing maximum bus voltage and performing a series of branch exchange operation concurrently	Heuristic method	Branch exchange type algorithm	Large-scale distribution networks	Convergence speed is accelerated. Suitable for large distribution systems.	Method is applicable only for the radial networks. Depends on load flow.

performed. Again in 2011 [42] they proposed a Hybrid Genetic-Fuzzy Algorithm (GA-Fuzzy) for optimal volt/var/Total Harmonic Distortion (THD) control in distorted distribution systems serving non-linear loads. Load interval division (over a 24 h period) and optimal scheduling of LTC and switched shunt capacitors for simultaneously minimizing Energy Losses and improving the power quality were performed using Genetic Algorithms with Fuzzy Reasoning and the non-linear load flow was solved by using a Decoupled Harmonic Power Flow Algorithm.

In this way the Gradual evolution in the direction of making loss minimization by Capacitor Placement superior has been revealed in Table 1.

Thus it can be seen that researchers have included various techniques to make the work of loss reduction by Capacitor Placement more effective. Such as:

1. Mixed-Integer Programming [44].
2. Linear Programming [45].
3. Nonlinear Programming [7–9,12–14,46].
4. Genetic Algorithms [47].
5. Ant Colony Search [50].
6. Artificial Neural Networks [52].
7. Tabu Search [49,51,53].
8. Particle Swarm Optimization [41,48,53–55].
9. Fuzzy Set Theory [56].
10. Simulated Annealing [64,65].

It is found that in this method of loss reduction along with size, location and methodology, one has to also deal with cable size, number of capacitors etc. and utility has to bare extra cost of capacitors and for capacitor placement techniques. Apart from this, losses due to the in-phase component of current are not appreciably changed by the application of capacitors; it only deals with reactive component of current.

4. Network reconfiguration

This section contains those publications which are related to loss reduction by using Network Reconfiguration which was found to be generally applicable in low voltage Distribution networks. It is a very imperative approach to save the electrical energy. Distribution systems consist of groups of interconnected radial circuits. The configuration may be varied via switching operations to transfer loads among the feeders. Two types of switches are used in primary distribution systems. They are normally closed switches (sectionalizing switches) or normally open switches (tie switches). Both types are designed for protection and configuration management. Network reconfiguration is the process of changing the topology of distribution systems by altering the open/closed status of these switches. Reconfiguration is applied for:

1. service restoration under faulty conditions,
2. load balancing to
   a. relieve overload on networks and
   b. improve voltage profile
3. planning outages for maintenance and
4. loss minimization.

The switching operation is the basic control action in network reconfiguration. A switching operation consists of closing the switch in an opened branch and opening the switch in a closed one keeping the network configuration radial. However, since there are many candidate switching combinations in the system, the feeder reconfiguration is a complicated problem. The discrete nature of the switch values makes it a discrete optimization

problem. The discrete nature of the switch values and radiallity constraint prevent the use of classical optimization techniques to solve the distribution reconfiguration problem. Therefore, most of the algorithms in the literature are based on heuristic search techniques by using either analytical or knowledge-based approaches. As per the method to handle the reconfiguration process one can categorize the algorithms in two types:

1. *Branch Exchange Type*—The system operates in a feasible radial configuration and the algorithm opens and closes candidate switches in pairs.
2. *Loop Cutting Type*—The system is completely meshed and the algorithm opens candidate switches to reach a feasible radial configuration.

Most of the literatures reveal the branch exchange type algorithms to minimize the losses by various methods. Loss reduction in the distribution system by reconfiguration was first proposed in 1975 by Merlin and Back [57] by a branch-and-bound method for distribution systems which was later in 1989 modified by Shirmohammadi and Hong [58]. Thereafter considerable researches have been conducted in this field which is summarized in Table 2.

So after going through a deep bibliographical Survey it can be observed that to make the Network Restructuring more effective various techniques such as Particle Swarm Optimization [80–84], Constrained Decision Problems Approach (CDPs) [85], Genetic Algorithm [86,87], Tabu Search [88,89], knowledge based expert system [90–92], Simulated Annealing [93–96], Single Loop Optimization [97], Ant Colony Search Method [98–100], Harmony Search Algorithm [101,102], Mixed-Integer Convex Programming [103], Mixed Integer Linear Programming [104,105] have been used by researchers.

The method of Network Restructuring was found to be a complex decision-making process for dispatchers to follow, it often requires extensive numerical computation and it also affects the coordination of the protective devices. In the aforementioned work on feeder reconfiguration, it is usually assumed that the protective devices are still properly coordinated when the feeder configurations are changed by switch operations but actually protective device planning and coordination are usually carried out for a fixed configuration [106]. Frequent changes in configuration can trigger outages or cause transient problems. Apart from this although the methods mentioned above do not have good convergence property most of them are used due to less computation time requirement for smaller systems. Despite the fact that all methods used above guaranteed that the optimal solution will be achieved, they do provide high-quality precise solutions and may lack in accuracy. Maximum techniques suffer to a certain extent, from scaling the problem to a finite number of switches, typically found on realistic distribution systems for larger systems, the computation time is prohibitively high and may not be suitable for real-time operation.

5. DG allocation

This section contains those publications, which are related to loss reduction by using DG allocation which depends on the availability of Distributed sources (if it is a Renewable Source). DG can be defined as “The generation of electricity from facilities that are sufficiently smaller than central generating plants so as to allow interconnection at nearly any point in a power system.” [107]

Recently the penetration of Distributed Generators (DG's) into distribution systems has been increasing rapidly in many parts of the world. Integration of DG into an existing utility can result in several benefits such as:

- reduced environmental impacts,
- increased overall energy efficiency,
- relieved transmission and distribution congestion,
- voltage support,
- exploitation of the renewable resources, such as wind, solar, hydro, biomass, geothermal and ocean energy and
- line loss reduction.

Distributed generators are very much beneficial in reducing the losses effectively compared to other methods of loss reduction. The main reasons for continuous growth in the penetration of DG in power network are:

- the environmental concerns,
- constraints on building new transmission and distribution lines,
- technological advances in small generators,
- power electronics and energy storage devices for transient backup and
- increasing public desire to promote “green” technologies based on renewable-energy sources.

It is also observed that improper allocation or sizing of DG can counter effect the system. The rise of DG is shifting the grid archetype away from the traditional centralized systems that have long been the basis for grid operation. As per the type, DG will have both positive and negative impacts on distribution networks as mentioned in Table 3.

Thus the problem of DG planning has recently received much attention by power system researchers so as to garner the maximum benefit from this upcoming power generation technology without violating the existing power system infrastructure. Various efforts taken by researchers in this method of loss minimization are summarized in Table 4.

In this technique of loss reduction by DG allocation also researchers have included various advanced techniques such as BEE Colony Algorithm [127], Mixed Integer Non-Linear Programming [128], Exhaustive Load Flow (ELF) Method [129], Particle Swarm Optimization [130–138], Fuzzy-Genetic algorithm [139,140], Hereford Ranch Algorithm [114,141], Ant colony search [76,142–145], Differential Evolution Approach [146], Heuristic Curve-Fitted Technique [147].

From the literature it may be considered that this promising method of Loss Minimization is getting wide attention due to its very important benefit that it minimizes the network loss along with the provision of electrical energy supply to fulfill the crises of demand. So researchers are trying to investigate new techniques to implement this method with maximum benefit.

Table 3
Impacts of DG allocation on distribution system.

Type of impact	Non-renewable DG	Renewable DG
Environmental		✓
Voltage stability	✓	✓
Reverse power flow	✓	✓
Reliability	✓	
Deferring upgrades of power system	✓	✓
Reduction of electricity tariff	✓	✓
Reduction of green house gases		✓
Cost saving	✓	✓
DG allocation flexibility	✓	
Loss minimization	✓	✓

Table 4
Gradual evolution in DG placement method.

Author	Type of loss	Prominent feature	Optimization approaches/ techniques	Optimization function/basic principle	Network	Achievements/merits	De-merits
Rau and Wan [108]	Minimization of losses, VAr losses, or Loadings in selected lines.	Proposed second order algorithm to compute the amount of resources in selected nodes to achieve the desired optimizing objectives.	Analytical approach	Objective function = min $\sum$ power loss	Meshed Distribution network	The objective is reduction of network losses, VAr losses, or loadings on selected lines.	Lengthy iterative procedure. No assurance of convergence. Not suitable for larger realistic system in terms of computational requirements (memory and speed).
Willis [109]	Active and reactive power losses	Analyzed the impact on feeder losses by DG installation by using 2/3 rule often used in capacitor placement on distribution systems.	Analytical Approach based on 2/3rd rule for Loss minimization	Zero point analysis	Radial Distribution network	Analysis was undemanding and easy to apply	Approach may not be functional in case of variable load conditions.
Mutale et al. [110]	Active and reactive power losses	Proposed two new loss allocation schemes one based on the allocation of marginal losses and the other on the allocation of total losses.	The substitution method	The objective of method is to derive a relationship such that losses can be expressed directly in terms of injections.	Real network based 265-node generic distribution system model.	Proposed loss allocation coefficients can be positive or negative therefore can recognize the presence of counter-flows due to the presence of DG.	Fixed components of loss are not considered.
Méndez et al. [111]	Active and reactive power losses	Provides annual losses variation due to DG	Analytical approach	Objective of the study was to quantify the impact of that DG allocation by considering aspects such as DG penetration level, DG dispersion, DG technologies, Generation mix by locating optimal DG penetration from losses point of view	Radial Distribution network	Loss minimization.	Complicated for large distribution systems.
Yiming Mao et al. [112]	Active and reactive power losses	Provides switch placement scheme to improve the system reliability and the losses by DG placement	Graph-based algorithms, which incorporate direct load control, are developed to locate switches.	The switch placement problem is formulated as a non differentiable, multi objective optimization problem.	394-bus radial distribution systems	Customer priority is also considered in problem. Applicable for unbalanced distribution networks with single or multiple distributed generators.	Computationally inexpensive in terms of memory and speed, robust, with moderate computer requirements.
Caisheng Wang et al. [113]	Power losses	Determine the optimal location to place a DG in radial as well as meshed systems to minimize the power loss of the system considering total power penetration from DG units.	analytical method	To find the optimal bus for placing DG in a networked system based on bus admittance matrix, generation information and load distribution of the system.	Radial as well as meshed systems	Fast. No convergence problems involved.	Not suitable for large systems. DG size optimization is not considered. Ignored economic and geographic considerations.
Mithulananthan et al. [114]	Power losses	Both the optimal size and location are obtained as outputs from the genetic algorithm toolbox.	Genetic algorithm	Objective function is based on the power loss in line $i-j$ $S_{\text{loss}ij}=S_{ij}+S_{ji}$	Radial distribution system	Considered discrete as well as continuous parameters.	Lack of accuracy when high-quality solution is required
Gandomkar et al. [115]	Power losses	HRA uses sexual differentiation and selective breeding in choosing parents for genetic string.	Hereford ranch algorithm	The objective function is, Min $f=\min(P_{r,\text{ loss}})$	34 –bus radial distribution system	Less number of iterations. Robustness	Premature convergence, excessive convergence time
Acharya et al. [116]	Active and reactive power losses	To calculate losses and to find out the optimal location of DG	Analytical Method	The objective function is based on sensitivity factors of active power	16, 33,69 bus radial distribution system	No Convergence problem, fast in calculation of the losses	Do not meet robustness requirements

Table 4 (*continued*)

Author	Type of loss	Prominent feature	Optimization approaches/ techniques	Optimization function/basic principle	Network	Achievements/merits	De-merits
Víctor et al. [117]	Power losses	Provides an approach to compute annual energy losses variations when different penetration and concentration levels of DG are connected to a distribution network.	Analytical method.	DG impact on losses was measured as the difference between losses in the considered scenario and losses in the base case (without DG).	Radial distribution system	Evaluated the losses on an annual basis, Results show that energy losses variation, as a function of the DG penetration level, presents a characteristic U-shape trajectory.	No-load losses, nontechnical and commercial losses are not considered.
Fracisco et al. [118]	Active and reactive power losses	Defined new relevant *Line Loss Index (LLI)* and observed the effect with respect to various DG penetration levels, DG dispersion and DG technologies as well as different power factors.	Analytical method.	*Line Loss Index (LLI)*	Radial distribution system	He pointed out some results like (i) For low DG penetration level, losses decrease but for higher penetration level losses marginally increase (ii) Reactive power loss curve is convex and (iii) Minimum active power loss levels are reached if DG is sufficiently dispersed	Considered only steady state capacity of DG
Hedayati [119]	Power losses	This method is based on the analysis of power flow continuation and determination of most sensitive buses to voltage collapse.	Continuation method and a direct method	$Q_{\text{loss}} = \left(\frac{(P_{\text{load}}-P_{DG})^2}{V^2} + \frac{(Q_{\text{load}}-Q_{DG}Q_{DG})^2}{V^2}\right) X_{\text{line}}$	34-bus test system	Improvement of voltage profile. Reduction of power Losses, Permit an increase in power transfer capacity, maximum loading, and voltage stability margin.	Computationally demanded
Thukaram et al. [120]	Power and energy losses	Identify the best place to install a new DG for a projected load increase	Analytical approach	Relative Electrical Distances (RED)	20 node, 66 kV system, a part of Karnataka Transco.	This approach will help to identify the new DG location(s), without the necessity to conduct repeated power flows.	Considered only real power losses.
Tuba Gozel et al. [121]	Power losses	Sensitivity factor is employed for the determination of the optimumsize and location of distributed generation so as to minimize total power losses by an analytical method without use of admittance matrix, inverse of admittance matrix or Jacobian matrix.	Analytical Approach	Formulated loss sensitivity factor based on the equivalent current injection	Radial distribution system	Method is in close agreement with the classical grid search algorithm based on successive load flows.	Computationally demanded
Atwa et al. [122]	Power and energy losses	Determining the optimal fuel mix of different types of renewable DG units in order to minimize the annual energy losses in the distribution system.	Probabilistic-based planning technique	The planning problem is formulated as mixed integer nonlinear programming (MINLP), with an objective function for minimizing the system's annual energy losses	Typical rural distribution system with different scenarios, including all possible combinations of the renewable DG units.	Guarantees the optimum allocation of the renewable DG units for all possible operating conditions. The objective function can be expanded to accommodate additional terms, such as capital and running costs of the DG units.	Lack of accuracy when high quality solution is required.
Karar Mahmoud et al. [123]	Power losses	Best location and size for system stability improvements.	Analytical approach	Stability index criterion. The objective function is formulated with full consideration of both quality and inequality constraints.	90 bus test system	Proved that calculating minimum system losses is not necessary to achieve coherence improvement for the voltage stability problem.	Not suitable for complicated situations.
Akorede et al. [124]	Power loss	These objective functions were first fuzzified to evaluate their imprecise nature and then transformed into a single multi-objective function, before it was finally solved	*Genetic Algorithm* (GA).	Objective functions considered in the study were maximization of the system loading margin as well as the DISCO's profit.	Meshed power systems	Determining the optimal capacity and location of DG units	GA is known to be very good at finding good global solutions but not so efficient in determining the absolute optimum
Hung et al. [125,126]	Active and reactive power loss.	Single and multiple DG allocation	*Analytical Method*	*Exact Loss Formula*	16, 33,69 bus radial distribution system	No Convergence problem, fast in calculation of the losses	Do not meet robustness requirements

Table 5
Summarized comparison of three loss minimization methods.

Loss Minimization Method	Benefits	Drawbacks
Capacitor placement	Line loss reduction. Control of power flow. Improvement of stability. Voltage profile management. Power factor correction. Source of reactive power Loss minimization.	Losses due to only out of phase components of currents i.e. reactive currents can be reduced. Along with size, location and methodology one has to also deal with cable size, number of capacitors etc. Utility has to bare extra cost of capacitors and for capacitor placement Methods.
Network restructuring	Line loss reduction. Load balancing. Provides protection to isolate a fault.	Complex decision-making process. Requires extensive numerical computation Affects the coordination of the protective devices. May not be suitable for real-time operation.
DG allocation	Line loss reduction. Source of Energy. Reduced environmental impacts. Increased overall energy efficiency. Relieved transmission and distribution congestion. Voltage support. Deferred investments to upgrade existing generation, transmission and distribution systems.	Improper allocation or sizing of DG can counter effect the system. DG planning. Causes reverse power flow in Distribution System which is traditionally designed for unidirectional power flow.

Table 6
Impacts of three loss minimization methods.

Impacts of methods	Capacitor placement	Network restructuring	DG allocation
Loss minimization	✓	✓	✓
Reliability	✓	✓	
Cost saving	✓		✓
Voltage support	✓	✓	✓
Demand side management		✓	✓
Affects protection system		✓	✓
Green power			✓
Load balancing		✓	✓

6. Comparative analysis

The prolonged study of all above mentioned Loss Minimization Methods reveal the comparative analysis given in Table 5 and the various impacts are summarized in Table 6.

7. Conclusion

This paper provides a bibliographical survey of the state-of-the-art of three basic loss minimization techniques such as (i) Feeder Reconfiguration, (ii) Capacitor Placement and (iii) DG Allocation used in distribution system, with a profound review of pertinent background, realistic requirements, the current status and competent techniques. It is based on many research articles published from the past 3 decades so that the detailed progressive research in this field can be summarized. The citations listed in this bibliography provide a representative sample of contemporary technical assessment pertaining to the improvement in efficiency of the distribution system by achieving power saving through loss minimization. Periodic Bibliographic updates on this topic will be useful as the power system continues to evolve.

Each method mentioned in this survey has been utilized to solve problem with various and limited objectives and constraints. Distribution system Loss Minimization techniques discussed in this literature as summarized in Tables 1, 2, 4 and 5 are leading to the following conclusions:

(i) Capacitor Placement Method which is especially applicable in High Voltage networks is most reliable and simple to implement. However apart from loss minimization, shows limited advantages as compared to DG allocation Method.
(ii) Network Reconfiguration which is found to be applicable in low voltage distribution systems is most economic but requires complicated controlling techniques. The reconfiguration involves many candidate-switching combinations which makes it a complicated combinatorial, non-differentiable, constrained optimization problem. It often requires extensive numerical computation and it also affects the coordination of the protective devices. Method is efficient but shows limited payback.
(iii) DG allocation is more focused to achieve interconnection when small generators exist (for instance, when isolated wind farms or small photovoltaic plants enter the distribution network) is most efficient and Shows perceptible potential towards loss minimization as along with loss minimization it serves many other benefits as explained in Section 5. However it faces problems towards implementation and installation. Due to the lake of effective benefit harnessing techniques this method is found to be least reliable. However researchers are trying hard to locate superior techniques to exploit all possible benefits of DG Allocation.

For the Distribution system operators the main hurdles are the implementation and reliability of the loss minimization technique. However with the view of environmental concerns and energy crises DG allocation is found to the best solution for the Distribution Loss Reduction.

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